HYDROPROOF ACOUSTIC EMISSION FOR PREDICTION OF FAILURE BEHAVIOR IN COMPOSITE PRESSURE VESSELS

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INTRODUCTION

The hydroproof acoustic emission (HAE) testing, which is acoustic emission (AE) testing during hydroproof testing, has been investigated as a robust tool to evaluate the structural integrity of the pressure vessels not only considering defects existed before the hydroproof testing but also considering damages occurred during the hydroproof testing[1,2]. In the HAE testing of a filament-wound composite pressure vessel, what plays the most important role is AE signatures which are elastic waves produced by the growth of damages and propagated through the vessel in a form of very dispersive Lamb waves and finally monitored by AE sensors, since the failure behavior of the vessel is inferred from these signals[3]. Thus, there are naturally two key issues in the HAE testing; 1) determination of the optimal mode of elastic waves to be monitored during the HAE testing, and 2) processing of AE signals to predict the failure behavior of the vessel. Here, we present our efforts to develop a systematic procedure of the HAE testing for the prediction of failure behavior in composite pressure vessels, addressing these two key issues together.

DETERMINATION OF THE OPTIMAL MODE OF ELASTIC WAVES

Specimens

In this work, we have used 6 filament-wound composite pressure vessels which are composed of cylindrical center (with the outside diameter of 10 inch and the length of 27.5 inch) and two domes where steel bosses were inserted. The vessels were wound using T800 carbon fiber over the insulation rubber into two layers; an 1.3 mm thick helical layer with the fiber orientation of ±30° and an 1.3 mm thick hoop layer with the fiber orientation of 90°.

Experiments

The optimal mode of elastic waves to be monitored in the HAE testing would be the mode of elastic waves that can propagate up to a certain distance enough to cover the surface of the vessel along all directions. To investigate the propagation characteristics of elastic waves in the vessel, an acousto-ultrasonic experimental set-up as shown in Fig. 1 was used.

In this experiment, a filament-wound composite pressure vessel (NSTEB 96-1) was filled with water and pressurized by a hydraulic pump to about 700psi which produced matrix cracking in the vessel. And the elastic wave was generated by a broad-band ultrasonic transducer with the center frequency of 500kHz (Krautkramer B0.5S) which was driven by a high energy ultrasonic pulser (Ritec RAM-10000) on the surface of the vessel. Once this elastic wave propagated through the vessel, the propagating wave was detected by a broad-band AE sensor (Digital Wave B1025) at 105 different locations (along 7 different propagation directions, θ from 0° (along hoop) to 90° (along axis), and at 15 different propagating distances, d from 50 mm to 400 mm along each direction). Then received signals were transferred to a modal-based AE signal processing system (Digital Wave FWD-4000) for further waveform analysis to find out the frequency component, wave speed, and the maximum possible propagating distance.

Waveform Analysis

Fig. 2 shows the result of waveform analysis for elastic waves received at d = 250 mm with θ= 0° (Fig. 2.a), 45° (Fig. 2.b), and 90° (Fig. 2.c). As the elastic wave propagates through dispersive medium like the vessel, there can be easily observed the separation of wave groups which is not apparent in the cases where the propagation distance is relatively short. The "A" denotes the wave groups with high propagating velocities, and "B" represents the wave groups with low speeds. In the case of the elastic wave propagating along hoop (Fig. 2.a), the part "A" carries the waves of high frequency components (with center frequencies at 520kHz and 210kHz), while the part "B" contains the waves of low frequency components (from 210kHz to 270kHz). The similar behavior can be seen in Fig. 2.b and Fig. 2.c, even though the specific frequency components are varied according to the propagation direction.

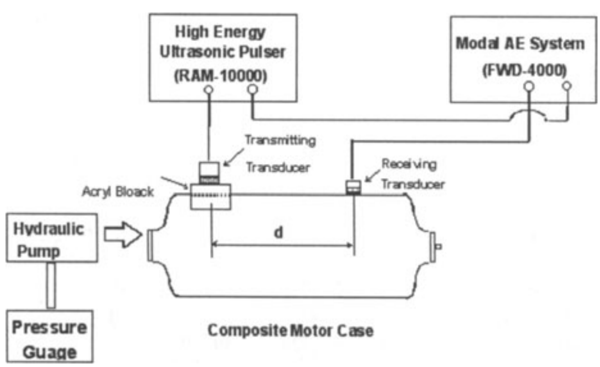

Fig. 1. The acousto-ultrasonic experimental set-up to investigate the propagation characteristics of elastic waves in the vessel.

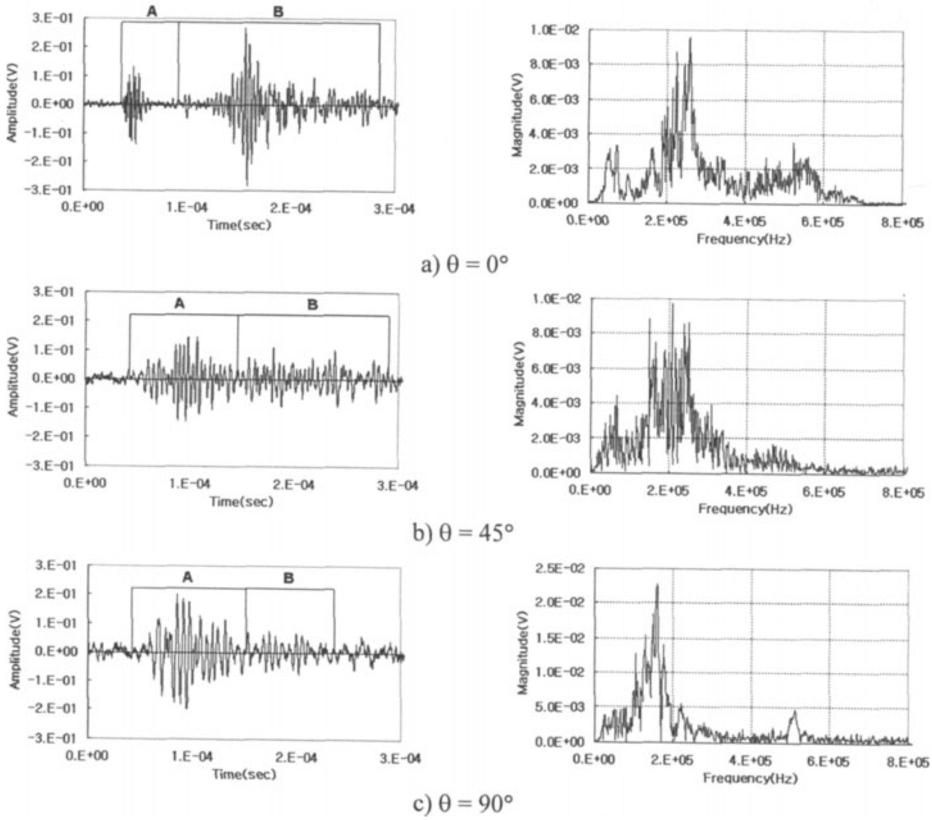

Fig. 2. Waveforms and corresponding frequency spectra of elastic waves received at d = 250 mm with; a) θ = 0°, b) 45°, and c) 90°.

In the cases where the propagation distances are even greater, the frequency components higher than 250kHz are attenuated to disappear, and only the low frequency components are carried by the “A” and “B” parts.

Determination of the Optimal Mode

By performing the waveform analysis for the received signal at 105 different locations, we can measure the maximum propagation distances of specific frequency components of elastic wave in the vessel along a certain propagation direction, as shown in Fig. 3. There are only 3 components that propagates along all directions. The component of 500kHz propagates about 300mm along hoop direction and attenuates very rapidly along other propagation directions. While, the components of 210kHz and 170kHz show the maximum propagation distances around 400mm in the all propagation directions.

To measure the velocity surface of the vessel, a band pass filtering (with the bandwidth from 160kHz to 260kHz) has been applied to the received signals to produce the tone-burst signatures. Then, by measuring the time delays according to the increase in the propagating distances along various propagation distances, the wave speeds of the narrow-band elastic waves (corresponding to the part “A” in Fig. 2) with the center frequency of 210kHz were measured as shown in Fig. 4, where the anisotropy in the wave speed can be observed, as expected.

From this investigation mentioned above, the optimal mode of the elastic wave to be monitored in the HAE testing is turned out to be that with the central frequency component of 210kHz, since this component propagates more than 400mm in the vessel along all of the directions without any significant attenuation.

PREDICTION OF THE FAILURE BEHAVIOR

Experiments

As shown in Fig. 5, 4 kinds of experiments were originally planned for each vessel. In the 1st and 2nd HAE testing which was conducted using the HAE testing system as shown in Fig. 6, vessels were filled with water and pressurized with the load-hold-unload loading cycle shown in Fig. 7. During the HAE testing, AE generated by the pressurization and damages from it was monitored by 9 narrow-band AE sensors with the center frequency of 150kHz (Physical Acoustic Corp. R15) attached to the vessel, and received AE signals were processed by a AE signal processing system (PAC Spartan 2000) to extract AE parameters in a real time fashion. In the impact testing, low speed impact was applied to the vessel by dropping a steel ball. In the final burst testing, a high power hydraulic pump was used to burst the vessels with the ramp-to-failure monotonous loading cycle.

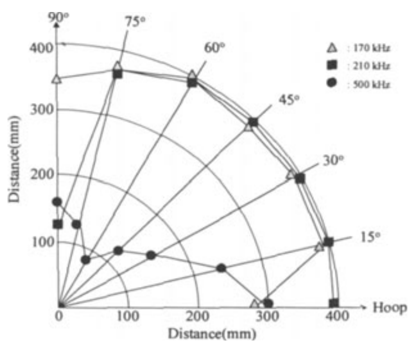

Fig. 3. The maximum propagation distances of elastic waves with specific frequency components along various propagation directions.

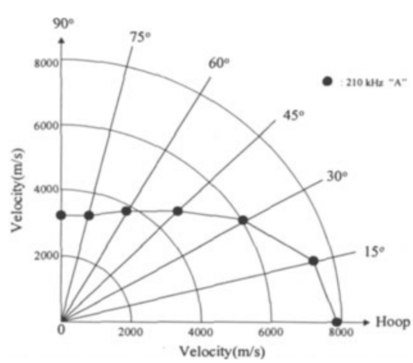

Fig. 4. Velocity surfaces for the elastic wave with the central frequency of 210kHz.

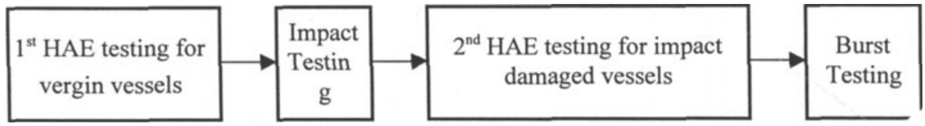

Fig. 5. Sequence of experiments performed to composite pressure vessels.

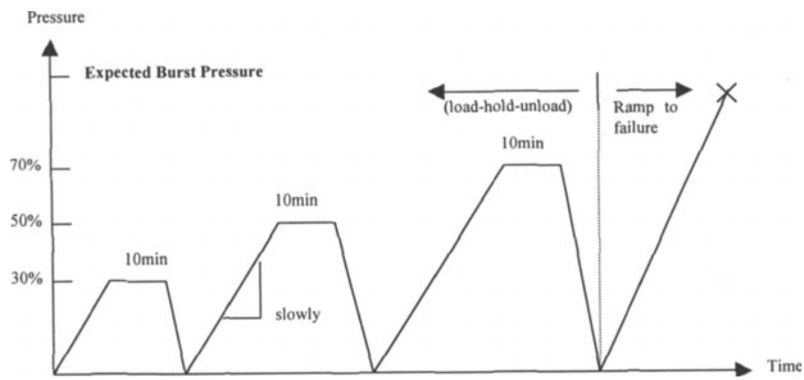

Fig. 6. Schematic representation of the HAE testing system.

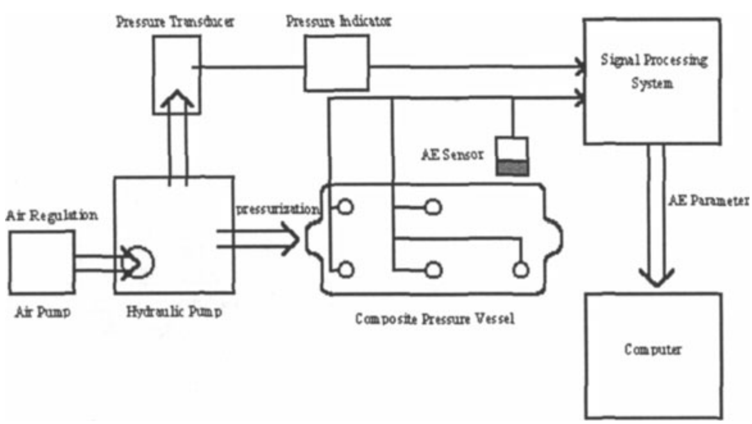

Fig. 7. Loading cycles used in the HAE testing and the final burst testing.

Results

For two specimens of NSTEB 96-2 and NSTEB 96-3, burst pressure has been expected around 3500psi. Thus, the 1st step proof pressure in the 1st HAE testing was chosen to be 1000psi which is approximately 30% of the expected burst pressure. But, unfortunately during the 1st step loading, the fiber breakage (FB) followed by delamination in the hoop layer was occurred in the NSTEB 96-2 sample, and the final failure due to the after-boss-pull-out (ABPO) in the NSTEB 96-3 sample. Experienced with these unexpected failures, the burst pressure for the remained 3 samples (NSTEB 96-4,5,6) was adjusted to 1400psi. Under this condition, all 4 tests were sequentially run for the NSTEB 96-4 specimen, while 3 tests except the impact test

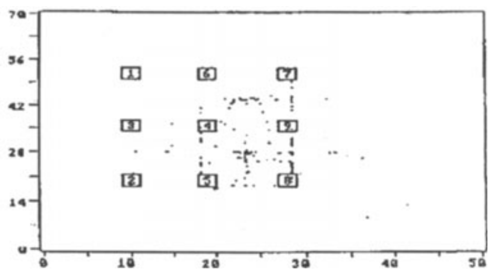

Fig. 8. Source location of AE events related to the fiber breakage in the NSTB 96-2 vessel.

were performed for the NSTEB 96-5 specimen. In the case of the last specimen, NSTEB 96-6, the fiber breakage was also occurred in the 1st HAE testing, so this specimen was directly put into final burst testing without the impact testing and the 2nd HAE testing. From the extensive examination on the HAE data, we have developed a systematic procedure for the interpretation of HAE data from which the failure behavior in the vessel can be predicted.

Location of Failure Sites

The location of failure growing sites in the vessel was reasonably determined by the simplified AE source location technique where the anisotropy in the wave speed of the vessel was ignored. For example, in the NSTEB 96-2 vessel fiber breakage in the hoop layer was observed in the 1st loading cycle of the 1st HAE testing. Fig. 8 shows the result of the AE source location where the large amount of AE events were activated at the site of fiber breakage (center of the rectangular formed by sensors 4,5,8 and 9).

Identification of Failure Modes

From the careful investigation of HAE data related to 3 failure modes (fiber breakage, matrix cracking, after boss pull out) in vessels, we have found that the distribution plot of the amplitude of AE events (which is called the "amplitude distribution plot") would be served as an efficient tool for the identification of failure modes. Fig. 9 shows examples of amplitude distribution plots for 3 different failure modes. The amplitude distribution plot of the fiber breakage appears in a symmetric bilateral triangle (Fig. 9.a), while that of the matrix cracking forms an non-symmetric triangle which implies the occurrence of AE events with low amplitudes in the greater portion (Fig. 9.b). For the after boss pull out, the shape of the amplitude distribution plot looks similar to that of the matrix cracking, but the former can be easily discriminated from the latter by the AE events with very high amplitude up to 100dB (Fig. 9.c).

Prediction of Other Failure Behavior

Final burst location and pressure are very crucial information in the prediction of failure behavior in the composite vessel. Our initial examination on the HAE data demonstrates the possibility of the determining the moment and the location of the final burst from AE events activated intensively right before the final burst. Further careful investigation on this is currently being undertaken. In addition, further study on prediction of the final burst pressure and the effect of impact damage on the failure behavior will also be carried out in the near future.

CONCLUSIONS

In this work, we have developed a systematic procedure of the HAE testing for the prediction of failure behavior in the filament-wound composite pressure vessels addressing two key issues in the HAE testing; 1) determination of the optimal mode of elastic waves to be monitored, and 2) processing of AE signals to infer the failure behavior from them. The optimal mode of elastic wave for the HAE testing was successfully determined from the analysis of propagation characteristics of elastic waves in the pressurized vessel using the broad-band acousto-ultrasonic experiments. Prediction of some important failure behaviors in the vessel such as location of failure sites and identification of modes has also successfully been done from the extensive examination of the HAE data.

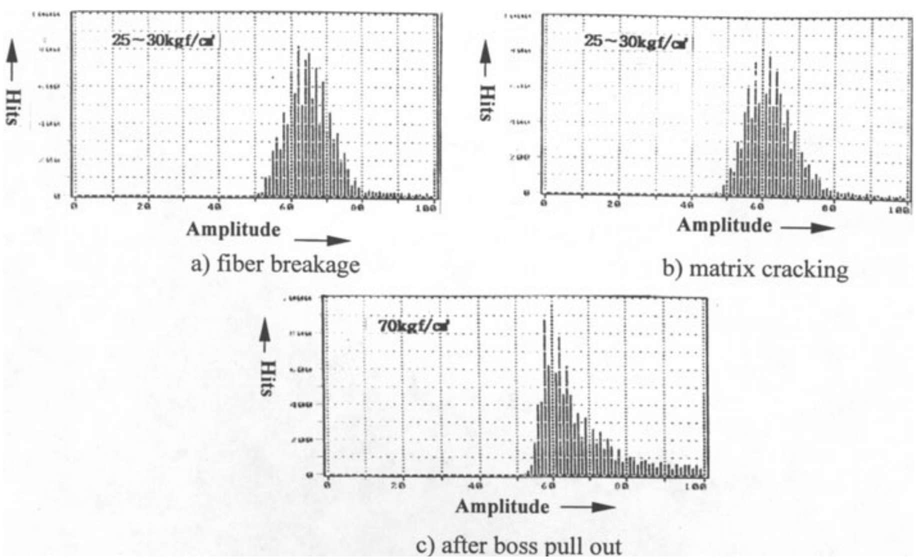

Fig. 9. Amplitude distribution plots for 3 different failure modes in the vessel; a) fiber breakage, b) matrix cracking, c) after boss pull out.

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